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Electronic Multidimensional Auctions and the Role of Information Feedback*

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***Abstract*- Traditionally, companies aiming to achieve competition among suppliers have used sealed bidding procedures in their sourcing processes. The advances in information technology and in particular the Internet now allow these companies to use different and more complex auction mechanisms. In particular multidimensional auctions are a natural extension of the standard sealed-bid auctions, but these auctions raise a whole host of issues that have been little investigated. In this article we focus on one of these issues, namely the role of information feedback given during the auction process. We describe various feedback policies and analyze the expected impact on the performance of the auction mechanism using the criteria of speed of convergence, allocative efficiency and Pareto optimality. This can help both researchers and practitioners in a more detailed and thorough analysis of electronic auctions.**

I. Introduction

Although electronic markets have been in existence for over a decade and especially the last few years have grown exponentially, paralleling the growth of the Internet, the accompanying theory is lagging behind substantially. In this paper we will make a start with developing a theory for a particular type of auction that holds great promise for practical applications, namely the multidimensional auction.

Although currently consumer auctions such as eBay, Onsale, Yahoo Auctions and Amazon Auctions are drawing most of the attention, the business-to-business auction market is expected to surpass the consumer auction market by several orders of magnitude (InformationWeek, 1999). In this research we will focus on the business-to-business context of electronic auctions.

In the majority of business-to-business transactions, the details of the transaction are not fixed in advance, but rather they are determined through some form of negotiation process. This negotiation process can take many forms, from unstructured bargaining between two parties to the high-speed market environments of stock exchanges to all kinds of auctioning procedures. In this paper we will focus on the latter category.

Traditional auction literature has dealt mainly with auctions being used as a mechanism to sell goods. In this case the bidders are the potential buyers and the bid taker is the seller and the auction mechanism is used to determine the price of the good being auctioned. If we were to model a common procurement setting (in other words using an auction as a mechanism to buy goods) with multiple suppliers competing for the buyer's order the roles of bidders and bid taker would be reversed. In that case the bidders are the sellers and the bid taker is the buyer.

This reversal from seller-driven to buyer-driven alone does not inherently change the auction and in principle traditional auction theory still applies. However in the reverse auction (i.e. procurement) case, the bid taker is much more likely to solicit bids that are based on more than just price alone. Bidders now would not submit a one-dimensional bid of just price, but instead submit a bid consisting of a vector of characteristics such as price, quantity, quality, delivery time and warranty. This provides another rationale for looking at multidimensional auctions, however this is an area that is little addressed in the current management, IS or economics literature.

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The paper is set up as follows: section II will review the existing literature on electronic auctions and multidimensional auctions, drawing from both the IS field as well as economics. Section III outlines the general approach we use to model multidimensional auctions. In section IV we turn our attention to the little-addressed role of information feedback given during the auction process. We outline several feedback policies and analyze the impact they have on the performance of the auction mechanism. Performance is judged on three criteria: speed of convergence, allocative efficiency and Pareto optimality. In addition, the concept of an informational balance of power is outlined. Section V concludes and also describes how these theories could be validated empirically.

II. Overview of Literature

An important issue when analyzing electronic markets (and auctions in particular) is the effect they have on the prices of traded goods and services. Bakos (1991) originally hypothesized that due to increased competition and less overhead, prices in an electronic market would be lower than in a traditional market. Lee (1998) and Crowston (1997) among others have empirically tested this reduced price hypothesis in several situations, but these tests have not led to unequivocal results as in some cases prices actually went up in an electronic market. Choudhury, Hartzel and Konsynski (1998) also showed mixed consequences of the usage of electronic markets and they suggest that the scope of the electronic market (i.e. which phases of the transaction are supported) is an important variable that has been overlooked thus far.

Koppius, Van Heck and Wolters (1998) analyzed an intermediate stage between a traditional and an electronic auction when they investigated the introduction of screen-based auctioning in a large Dutch flower auction. Traditionally the flowers were driven into the auction hall on carts, but the logistical complexities of this process led the flower auction to experiment with screen-based auctioning. Instead of physically showing the flowers, an image of the flower was shown. Koppius, van Heck and Wolters (1998) showed that in the new situation the worse product representation (as perceived by the bidders) caused a significant price drop.

Despite the obvious practical relevance, research specific to electronic auctions is not very extensive. Van Heck and Vervest (1998) provided a typology of web-based auctions, based on the numbers of buyers and sellers. In the business-to-business context under investigation here, we are dealing with procurement auctions and to a lesser extent sales auctions. Turban (1997) gave an overview of some of the products that are being auctioned electronically and outlined some potential benefits, such as cost reduction and inventory clearance. A much more extensive overview is given by Lucking-Reiley (1999). Wrigley (1997) suggested that electronic markets in general and auctions in particular will occur when one of the following characterizes the goods to be sold: perishability, scarcity, possibility to deliver electronically or to a geographically constrained market (such as second-hand goods for instance). Their hypotheses were partially confirmed by Van Heck, Koppius and Vervest (1998), who compared four electronic auctions on the Internet and identified some common success-factors, the most important ones being increased scale of the market for the seller and greater market visibility for the buyer.

With regards to the role of information technology when analyzing auctions, we take the following stance. Like Shapiro and Varian (1998), we contend that ICT does not so much change the fundamental characteristics of the general auction process, as the economic principles behind auctions are still valid, but rather it enables new trading mechanisms to be implemented that were previously unknown or infeasible. Examples include Drexler and Miller (1988), Rothkopf, Pekec and Harstad (1995), Varian (1995), Miller (1996), Clearwater (1996), Gomber, Schmidt and Weinhardt (1998) and Koppius (1998). For example, Drexler and Miller (1988) describe what they refer to as the ‘escalator bidding algorithm’. They liken bidding strategies to escalators: a bidder chooses the initial height of the bid (the step at which to enter the escalator) and the rate of increase per time unit (the speed of the escalator); also he can enter bids on different types of escalators at the same time that progress at different speeds. Clearly this sort of bidding strategy would be hard to implement without IT.

This view of IT’s role allows us to use results from (microeconomic) auction theory when analyzing electronic auctions. Most auction theory mainly deals with the traditional auction of an indivisible good (possibly multiple units of that good), with the auction process being conducted on price. The past few years some progress has been made in researching extensions to this framework, partly in response to criticism that the assumptions of a game-theoretic/mechanism design approach to auction theory are not very realistic in a practical setting. See Rothkopf and Harstad (1994) for an overview of such criticism.

The class of multidimensional auctions forms one very interesting extension to the standard auction framework. In these auctions, instead of consisting of just a single parameter (i.e. price), a bid consists of a vector of attributes such as quantity, quality, delivery time etc. in addition to price. When auctions are used for procurement, such parameters are generally not fixed in advance, but instead are determined by the bidding (sometimes called tendering) process. As argued before, this makes the multidimensional auction a very likely candidate to be used in an electronic business-to-business market, also because of the low cost of fulfilling the much higher informational requirements of such a mechanism.

There have been several authors who investigated auctions in a context of procurement or internal sourcing, which exhibits multidimensional characteristics as shown, although they have not always specifically identified it as multidimensional auctions per se.

Van Damme (1997) gives an overview of the theory and use of auctions as a procurement mechanism. Dasgupta and Spulber (1989/1990) showed that setting a fixed quantity to be procured is sub-optimal and that instead the decision of the quantity to be procured should depend on the received bids. They also investigated the multiple sourcing problem in which the quantity to be procured is to be distributed over multiple suppliers and gave an optimal two-stage mechanism for this case.

Bushnell and Oren (1995) looked at the problem of setting production levels and selecting an internal supplier for an intermediate product and described how theoretically a multidimensional auction could be used to set an efficient transfer price for that intermediate product.

Thiel (1988) was the first to specifically investigate multidimensional auctions. He showed that if the bid taker (i.e. the procurer) has a publicly known, fixed budget and does not value any savings, the multidimensional case can be reduced to the one-dimensional case of a normal auction. Unfortunately these assumptions are not entirely realistic from a practical point of view.

Che (1993) looked at three different auction mechanisms for two-dimensional auctions (on price and quality), based on actual practices at the US Department of Defense. He showed that under certain circumstances the three investigated mechanisms yield the same expected revenue and that in all circumstances, quality is either undervalued or overvalued from the buyer's point of view. In his analysis, he assumed that the costs of the bidding firms were independent. Branco (1997) extended Che's analysis by deriving an optimal auction mechanism for the more realistic case when the bidding firms' costs are correlated.

Cripps and Ireland (1994) approached the problem from a slightly different point of view when they investigated auctions in which the bid taker sets threshold levels for the various characteristics that are not known to the bidders. They analyzed three different bid evaluation schemes, partially based on the tendering of UK television licenses. The difference between the schemes was the order in which each bid was evaluated (price first, quality second; quality first, price second; price and quality simultaneously) and they found that the three schemes produced the same results.

Note that sometimes the terminology multidimensional auctions is used to denote combinatorial or combinational auctions (Rothkopf, Pekec and Harstad 1998). Analysis of these auctions generally focuses on bundling and valuation issues of bids and should therefore not be confused with issues related to the multidimensional auctions described here, although some progress is being made on unifying the two types (Koppius 1999).

III. A GENERAL MODEL OF MULTIDIMENSIONAL AUCTIONS

Consider the following simple procurement model in which there is one buyer (i.e. bid taker) and *n* suppliers (i.e. bidders). The bid taker has *K* attributes on which the buyer must bid in order for a bid to be valid, hence all bids must be *K*-dimensional vectors. The attributes may be any combination of monetary and non-monetary attributes. Possible attributes can include a fixed-price component, a variable-price component, payment schedule, quantity offered, various product quality attributes and issues such as warranty policies.

A bid by firm *i* is denoted by $\mathbf{b}_i = (b_{1,i};...;b_{K,i})$ with each separate $b_{k,i}$ denoting the level of attribute *k* in bid ***i***. The bid taker has a private utility function $U(\boldsymbol{b})$ that denotes the utility he derives from a bid; this function converts both monetary and non-monetary attributes into a utility. The bid taker can choose to reveal his utility function (either truthfully or not) or he can keep it secret and perhaps reveal different information.

Analogous to the reserve price in conventional auctions, the bid taker has several constraints $\beta_s(\boldsymbol{b})$ (s = 1,…,S) regarding the values of the attributes, resulting in a feasible bid region for the bid taker denoted by $\boldsymbol{BR}^*$. These constraints may be the just simple minimum or maximum values or more complex functions describing some of the tradeoffs between attributes (say for instance the maximum price increase for faster delivery, possibly dependent on the quality level). These constraints may or may not be communicated to the bidders, depending on how much private information the bid taker is willing to retain. The bid taker tries to maximize $U(\boldsymbol{b})$ s.t. $\mathbf{b} \in \boldsymbol{BR}^*$.

Similarly, each of the bidders faces several constraints $c_{i,t}(\boldsymbol{b})$ (t = 1,…,T) regarding the sets of attributes that he can offer, resulting in a feasible bid region for each bidder denoted by $\boldsymbol{BR_i}$. These are constraints that have to do with internal production function, minimum price levels etc. They are assumed to be private information, but not necessarily independent. In fact in this procurement context they are very likely to be quite strongly affiliated. Furthermore, each bidder has a utility function $\pi_i(\boldsymbol{b})$ which he tries to maximize s.t. $\mathbf{b} \in \boldsymbol{BR_i}$.

There are several different generic auction types the bid taker/auctioneer could employ and in particular the sealed-bid case is very common in practice. One of the reasons for this is that the open outcry model would be very costly in terms of communication unless the bidders all congregate in one place, which is rather cumbersome, particularly when dealing with a geographically dispersed set of suppliers. One of the disadvantages of a single-shot auction is that there is no opportunity for the bidders to react to other bids, but instead estimates of other bidders strategies have to be used. Speaking from a purely theoretical point of view, this should yield the same results, but in practice things often work out differently. For instance, market maker FreeMarkets Online claims on their website (www.freemarkets.com) that they achieve savings of up to 25% when using an English auction instead of a single-shot auction.

Therefore we focus on a multiple-round setting, so that bidders get a chance to update their initial bids, based on the information feedback they receive from the auctioneer. This line of reasoning is similar to one of the rationales for the FCC auction design (Cramton 1995). This not only gives the bidders the opportunity to react to other bidders, but more importantly they have more options to explore the highly complex bid space of multidimensional auctions with all its potential tradeoffs. The information feedback given to the bidders may include information on their own bid, such as their bid score or bid ranking, but also information on other bidders' bids. The information feedback may be public or private or a mixture of the two. The updating may occur synchronously, meaning that all bidders have to submit a bid before feedback is given and the next bidding round commences, or it may occur asynchronously, in which case it becomes an English variant of the multidimensional auction.

IV. THE ROLE OF INFORMATION FEEDBACK

To show the relevance of information feedback, we will first describe a very simple deterministic situation. Assume a procurement setting where there are two dimensions, namely cost and delivery time. There are two bidders competing for the order through an English auction. Bidder 1 can deliver at a cost of c_1=900 and delivery time d_1="on time". Bidder 2 on the other hand can deliver at a cost of c_2=1000, but can deliver d_2="early". Suppose the bid taker values earlier delivery at the cost equivalent of 10. If the bid taker truthfully reveals this information, the end result will be that bidder 1 will win with a winning bid of 989. However, suppose the bid taker were to tell the bidders he values earlier delivery by 90. Bidder 1 would still win, but now with a winning bid of 909 instead of 989. Although the example is not particularly realistic, since it assumes complete information on the bid taker's side for instance, it does show that different information feedback policies do have an impact on the outcome of the auction. Additionally it shows that sometimes the bid taker can profit from misrepresenting his private information. In general, misrepresentation is profitable for the bid taker when used to push the most efficient bidder to the limit, effectively by 'subsidizing' the second-most efficient bidder.

Another reason to investigate the effects of different auction feedback policies (other than utility of the bid) is that using a utility function sometimes is not possible or desirable. For instance, it may be illegal to misrepresent it (for instance in government procurement) or announcing a utility function may give monopoly power to one or more bidders. Or the bid taker simply may not have an explicit utility function, but instead only be able to do pairwise comparisons[1]. A third reason is that it is an area that has received little attention thus far, both from theorists and experimentalists (Kagel and Roth 1995, Ch. 7). Yet with the increasing popularity of auctions and in particular the more complex electronic auction mechanisms enabled by information technology, a theory on the effects of information feedback is necessary more than ever.

Any information feedback policy can be thought of to comprise as many as five categories of information elements:

1. Actual bids
2. Bid scores
3. Bid rankings
4. Bid taker's utility function
5. Bidder identities

The first category gives information regarding the bids themselves. This is usually done in conjunction with elements of categories 2 and 3, such as revealing the highest bid. An interesting hybrid policy would be to not reveal information about the bids received, but instead give each bidder a number of alternatives that would improve on their current bid (and perhaps top the current highest bid). This would make it easier for the bidders to spot mutually beneficial tradeoffs in the multidimensional space. See figure 1 for an illustration of such tradeoffs in a two-dimensional case with a bid being made on price and delivery time. Two iso-utility curves are drawn, one for an arbitrary bidder, one for the bid taker. The curves correspond to the utility of the bid being

[1] Note that using pairwise comparisons will only be equivalent to using a utility function when an unlimited amount of pairwise comparisons can be done accurately and with zero cost.

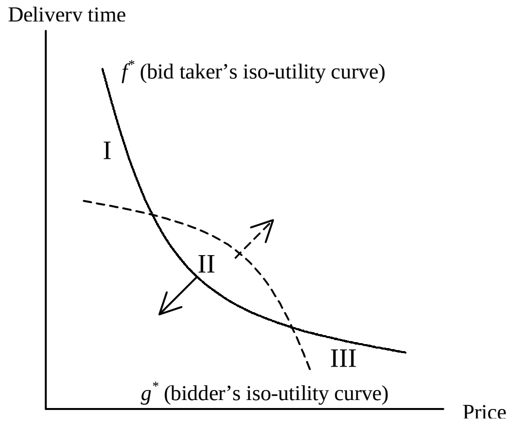

Figure 1: Mutually beneficial tradeoffs

made by that particular bidder, i.e. the bid made is at one of the intersection points of the two curves. The arrows indicate the direction of utility improvement for each party. The bid taker (i.e. buyer) prefers a lower price and a faster delivery time, the bidder (i.e. seller) prefers a higher price and a later delivery time. Areas I and III are areas in which any bid would yield increased utility for both parties. A bid in area II would yield decreased for both parties. A bid in the remaining areas would yield a utility increase for one party and a decrease for the other party. Note however that we have assumed no further restrictions on the attributes, such as a maximum price the bid taker is willing to pay or a minimum delivery time the bidder can meet for instance. These may prevent areas I and III from being feasible bids for both parties. Note also how this example illustrates some of the issues that arise in multidimensional auctions and not in the standard one-dimensional auctions on price (due to the zero-sum nature of standard auctions).

The second category refers to the revelation of the scores of a bid, with score being the bid taker's utility. Note that (bearing in mind the information manipulation example given earlier) the utility revealed need not necessarily correspond to the actual utility of the bid taker, since misrepresentation may be profitable. Also note that revealing a utility is only meaningful if the scale of the utility is (partially) known to the bidders.

The third category reveals information about the relative ranking of the bid among all bids received, based on the bid taker's (possibly misrepresented) utility. This information can be enhanced if the total number of bids received is revealed as well.

The information from the second and third categories in principle allows bidders to make partial inferences about the bid taker's utility function after a number of rounds. However, the bid taker can also choose to reveal some information about his utility function directly and that is the fourth category. He may choose to reveal the utility function entirely, but another option might be to reveal the direction of fastest improvement upon the current bid. This corresponds to the normal vector of the utility curve at the bid point (see also the arrows in figure 1).

The fifth category constitutes the revelation of the identity of the bidders. The identity of the highest bidder will generally only be revealed at the end of the auction, but it is of course possible to reveal the identity of the current high bidder during the auction. In other cases one may want to have a completely public auction in the sense that the identity of each bidder is known at all times.

To analyze the effects of different feedback policies on the performance of the auction mechanism, we need criteria by which to judge performance, as performance can be measured in different ways. We focus on three performance measures:

1. Speed of convergence
2. Pareto optimality
3. Allocative efficiency

Speed of convergence especially is an important issue in auctions where transactions need to occur at a rapid rate. A typical (one-dimensional) example is the Dutch flower auctions. Since these deal with very large volumes of perishable goods, each individual transaction needs to be completed quickly. Hence the adoption of the Dutch auction clock system that is capable of completing a transaction every four seconds (Kambil and Van Heck 1998). No other auction method can be expected to achieve this speed. In an auction of a rare painting on the other hand, speed of convergence is much less likely to be an issue, which makes an English auction a more likely choice.

Pareto optimality in a multidimensional auction is measured at the dyad level of (winning) bidder-bid taker. A (winning) bid is Pareto optimal if no feasible bid can be made which is a Pareto improvement, i.e. no mutually beneficial bids exist for the bid taker and that particular bidder. Note that this not necessarily means that the bid taker's utility is maximized.

Allocative efficiency is achieved when the most efficient bidder makes the actual winning bid. In standard one-dimensional auctions, allocative efficiency is achieved when the bidder with the highest valuation wins the auction. In the reverse case under consideration here, it means that the bidder with the lowest cost structure wins the auction. So a multidimensional auction is efficient if, given a winning bid, there does not exist a different bidder who could make a feasible bid (feasible for both parties) that would improve the bid taker's utility.

Loosely speaking, efficiency ensures that the eventual trade occurs between the 'right' trading partners, optimality ensures that the total surplus of that trade is maximized.

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It is important to note that a winning bid can be Pareto optimal, but not allocatively efficient and vice versa. An optimal, inefficient winning bid can occur when the winning bidder has Pareto-optimized his own bid relative to the bid taker's utility (no Pareto improvements possible, areas I and III in fig. 1 are not feasible), yet there may be a different bidder that could outbid him (allocative inefficiency), but that bidder has not made such a bid. A non-Pareto-optimal, allocatively efficient winning bid can occur when there are no bidders that could outbid the current highest bidder (allocatively efficient), yet his current bid could be Pareto improved upon (areas I and III in fig. 1 are feasible, yet not being bid in). In both cases, the complexity of the bid space and unfamiliarity with the bid taker's preferences lead to performance degradations that could be ameliorated by giving proper feedback.

If we look more closely at these three performance criteria, we can distinguish between two information-related aspects that influence these criteria: direction for improving the bid and a sense of competition among the bidders.

Optimality is something that has mainly to do with the shape of the utility curves: where do the regions of Pareto improvement lie? This requires information feedback about the direction in which to move the bid in order to achieve optimality.

Efficiency on the other hand has to ensure that the most efficient bidder wins, meaning that competition among bidders has to be fierce. The more information bidders have about their position relative to other bidders, the greater their perception of competition and therefore the more aggressive their bidding behavior.

Speed of convergence is improved by both kinds of information: more aggressive bidding (through a higher sense of competition) in a direction of fast improvement (through better direction information) will lead to a quicker convergence.

In summary, we have the following three propositions:

Proposition 1: Feedback that conveys more information about the direction in which to improve the bid will have a positive impact on the optimality of the auction.

Proposition 2: Feedback that conveys a higher sense of competition among the bidders will have a positive impact on efficiency of the auction.

Proposition 3: Both types of feedback will have a positive impact on the speed of convergence of the auction.

In Table 1, we outline several feedback policies. Based on the informational content with regards to direction and sense of competition of each feedback policy, in conjunction with propositions 1-3, each feedback policy is rated on the performance criteria of speed of convergence, optimality and efficiency. These are rough and qualitative ratings, as a useful (mathematical) formalization of the directional content and the sense-of-competitional content does not seem very likely. Note that we have left out feedback policies dealing with whether or not to reveal bidder's identity, as the effects of that are indeterminate to the best of our knowledge.

Feedback	**Speed**	**Optimality**	**Efficiency**
Bid highest? (yes/no)	-	-	-
1 alternative	-	o	-
n alternatives (n relatively large)	+	+	o
Rank of bid	o	-	+
Highest bid	o	o	+
All bids + ranking	+	+	+
Bid score + highest bid score	-	-	o
Bid score + all other bid scores	o	-	+
Bid taker's utility function	o	+	-
Direction of fastest improvement	+	+	-

Table 1: Feedback policies and the effect on auction performance

The performance measures outlined above all deal with the economic performance of the auction mechanism. As propositions 1-3 outline, more (appropriate) information will improve economic performance. However, this is a somewhat myopic view of auction mechanism performance. Auctions in general and especially in the business-to-business environment do not exist in a vacuum. They are embedded in a set of economic and social relationships that may be affected by the outcome of the auction and these relationships can have a large effect on the performance of future auctions (Smith 1989). This implies that the information revealed in one auction will influence future auctions.

For instance, if the bid taker were to reveal his utility function, not only would he possibly give monopoly rents to one or more bidders, but more importantly it would likely reveal sensitive competitive information about his internal cost and production structure. Bidders in future auctions can subsequently use this information against the bid taker. So even though the short-term effect on the economic performance of an isolated auction may be positive, the long-term effect may turn out negative due to performance losses in future auctions.

This leads us to introduce a concept we call the 'informational balance of power'. In every auction setting, each participants in this auction (either bidder or bid taker) has some information about the other participants. This means that there is a certain balance of power involved: do I know more about this participant than he knows about me?

The revelation of information by a participant can tilt this informational balance of power if something significantly new is learned from this by other participants. Specifically for information revealed by the bid taker, we have the following proposition.

Proposition 4: The information feedback policy that is chosen by the bid taker will be such that it preserves the informational balance of power.

V. Conclusion and further research

There is no doubt that electronic markets and electronic auctions in particular represent one of the fastest growing segments of electronic commerce. As the possibilities of information technology increase, more complex auction mechanisms become feasible, for which in many cases no theory exists.

In this article we have looked at one of these new auction types, namely the electronic multidimensional auction. In the multi-round setting that we analyze, an important issue both for theory and practice is the information feedback given during the auction. We have argued the relevance of this topic and described the elements of any information feedback policy. We have stated four propositions as to how these elements affect the auction mechanism performance measures of speed of converge, optimality and efficiency plus a more strategic aspect, namely the informational balance of power and illustrated these with several examples in Table 1.

Especially as business-to-business electronic auctions become more prevalent each day, careful attention has to be paid to the design of these auctions. The informational aspect described in this paper is one of these issues. While this is by no means a complete theory of all the informational aspects involved in designing electronic auctions, we do believe we have made some progress towards such a theory.

Subsequent research needs to address several things. The ratings in Table 1 have been arrived at through simple, somewhat ad hoc judgments. A more rigorous operationalization of the informational content of feedback is needed. Also, propositions 1-4 need validation. We are planning a series of laboratory experiments in the spring of 2000 to validate propositions 1-3. We will run an electronic multidimensional auction with student subjects bidding under various information feedback policies. Proposition 4 cannot be adequately validated in a lab experiment, since it is hard to reproduce the proper social settings that are crucial to analyzing the informational balance of power. We are currently negotiating with an electronic auction provider to either set up a field experiment testing proposition 4 or conduct a case study of a multi-round procurement auction to gain insight into participants' perception of the informational balance of power and changes therein. Hopefully the validation and further development of these aspects will help theorists and practitioners with the many design issues faced when developing and analyzing electronic auctions.

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